Removing the influence of rotor harmonics for improved monitoring of offshore wind turbines

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ABSTRACT
The ability to identify the dynamic properties of offshore wind turbines allows validating and updating numerical tools, which can be used to enhance the design. At the same time, these dynamic parameters can serve as a basis to continuously monitor the integrity of the machine. However, modal identification of turbines in operating conditions still poses some major issues, in particular in removing the rotor harmonic components, which are polluting the measured signals.
This paper will present and discuss some recent developments for removing harmonic components from operational wind turbine data. The possibility to track the evolution of specific modes is compared against classical techniques such as Time Synchronous Averaging and Cepstrum, which show limitations due to rotational speed fluctuations, amplitude modulation of the harmonic components and the interaction between the harmonics and the aerodynamic loads. The methodologies are firstly presented and then applied to real data of an offshore wind turbine installed in the Belgian North Sea. The ability to identify more accurately the modal parameters will allow improving the correlation with the varying environmental conditions and provide additional input data to validate numerical models.

KEYWORDS: Wind turbine, monitoring, offshore, automated modal analysis, harmonic removal.

1. INTRODUCTION

The size of commercial wind turbines has continuously increased in the last decades, going from 50 kW rated power machines to the current 5 MW ones with a rotor diameter of more than 120m. The structural growth and the trend of investing more and more on offshore installations pose serious challenges for the future and a thorough understanding of wind turbine dynamics is mandatory. On one side, dedicated aeroelastic simulation tools have been developed to aid engineers in the wind turbine industry to develop more advanced machines by simulating their dynamic response under different environmental conditions. By increasing the simulation accuracy, the performance and durability during the life time of the turbines can be more accurately estimated. On the other side, the ability to monitor the performance of the turbines remotely is of critical importance in particular for offshore installation, when operation and maintenance costs are significantly higher than for onshore turbines.
State-of-the art operational modal analysis techniques can provide accurate estimates of natural frequencies and damping ratios of structures in operating conditions. The identification of the modal parameters provides useful information for validating the numerical models but can also help assessing the integrity of the structure and monitor the evolution of damages. This methodology, firstly introduced in the '80s with the Natural Excitation Technique (NExT)[1], is widely applied to identify the modal parameters of structures in operating conditions in all the cases where the input forces cannot be measured so standard identification methods cannot be applied [2][3][4].
The application of OMA to an operational wind turbine is indeed attractive, as they are slender structures naturally excited by a stochastic force related to the wind turbulence. However, OMA can only be applied under specific assumptions which are violated by a wind turbine in operation so there are a lot of ongoing research studies to stretch the applicability limit of these methods. The first assumption of these assumptions is that the structure must be excited by uncorrelated steady state random noise in the frequency band of interest over the entire structure. This is not the case for wind turbines in operation, where the blade rotation introduces harmonics at discrete multiples of the rotational speed. In addition, periodicity and correlation of the aerodynamic forces exciting the structure introduce additional issues that cannot be treated with standard tone removal techniques [5]. Another limiting assumption is related to the linear time invariance of the structure during the analysis. On top of blade stiffening effects introduced by the centrifugal forces during rotation, the configuration of the wind turbine is

heavily modified by pitch and yaw control mechanisms. Wind intensity variations also generate invariances in the system by modifying the aerodynamic damping of the structure.

In this paper, different Operational Modal Analysis techniques will be applied to acceleration signals acquired on the tower of an offshore wind turbine in different operating conditions. Firstly, the identification algorithms will be used to identify a reference modal model when the turbine is in parked conditions. In this case, the rotor is idle or rotating at very low speeds so that the wind excitation can be considered as the ideal steady state random white noise. The results from different identification algorithm will be compared and discussed. Once a reference modal model is identified, an automated modal analysis algorithm is applied, allowing automatically processing long time histories with very limited user interaction. The ability of the method to track the evolution of a selected set of modes over time will be discussed. The same techniques are then applied to data acquired with the turbine in operation. The frequency-domain spectra will be compared with those of the turbine in parked condition to identify and quantify the influence of the harmonic components. Since the acquired data are limited to the tower, natural frequencies and mode shapes should remain the same as in parked conditions, so a direct comparison can be performed. The strong influence of the harmonics in the frequency range of interest can sometimes affect the ability of the methods to properly identify the modal parameters. The raw data will then firstly be processed using the automated identification tool. A reference modal model will be selected including only the structural modes and the possibility to automatically clean up the Campbell diagram from the numerical poles is investigated [6]. After evaluating this simple method, harmonic removal techniques such as Time Synchronous Averaging[7] and the Cepstrum Editing method will be applied [8]. After analyzing and testing these algorithms in combination with Operational Modal Analysis methods on a single 10 minutes dataset, they will be included in the automated processing and identification procedure. Their efficiency will be evaluated by assessing the ability to track the modes over the whole available time histories and to increase the success rate of identification for each mode.

The paper is organized as follows. In Section 2 the operational measurement campaign on the offshore wind turbine and the main objectives of the project in the context of which they are performed are discussed. Section 3 will present the results of the automated OMA procedure on the data acquired in parked conditions. In Section 4 the operational data will be discussed and the different harmonic removal techniques presented. Finally in Section 5 the automated procedure with filtering is analyzed and the results compared with those obtained on the same dataset but without any filtering.

2. OFFSHORE MEASUREMENTS

This paper presents the approaches and results of a long-term monitoring campaign on an offshore wind turbine. The measurement campaign is performed on one of the 55 Vestas V90 3 MW wind turbines at the Belwind wind farm. The wind farm is located at the North Sea on the Bligh Bank, 46 km off the Belgian coast [9]. Within the bigger OWI-project (ww.owi-lab.be) for which the measurement campaign is performed, the IWT OptiWind project was also launched, to sustain more fundamental research and validating the methods and results with real measurement data. The research activities aim at improving the design and concept of offshore wind park components and their serviceability by developing and validating dedicated numerical and experimental modeling tools. Moreover, the development of robust and effective Structural Health and Condition Monitoring techniques for offshore wind energy to reduce the O&M costs is also addressed. In this context, the main objective of the measurement campaign is to continuously monitor the vibration levels and the evolution of the frequencies, damping and mode shapes of the most dominant modes of the tower and foundation.

The tested wind turbine is placed on a monopile foundation structure with a diameter of 5 m and a wall thickness of 7 cm. The overall dimensions of the wind turbine as well as the geometrical characteristics of the installation are shown in Figure 1. For this measurement campaign only the tower and the transition piece are instrumented. 10 accelerometers are distributed over 4 levels. On the higher level, 4 sensors are placed to capture also tower torsion (Figure 2). Accelerometers have been selected to have high sensitivity (1V/g) and are able to measure very low frequency signals (0-250 Hz). This is necessary considering that the lower modal frequency of interest is expected to be around 0.35 Hz and the expected vibration amplitudes due to ambient excitation are very low.

The monitoring system is a Compact Rio system by National Instrument and is mounted in the transition piece. Acceleration signals are continuously acquired and data are sent every 10 minutes to the server installed onshore using a dedicated fiber running over the sea bed. The data acquisition system was programmed to acquire data at a sampling frequency of 5 kHz, which is way above the frequency range of interest. To also reduce the amount of stored data, a low-pass filter and a resampling at 12.5 Hz are applied. Finally, to have the data ready to be analyzed, a coordinate transformation is performed to align the measured accelerations with the axis of the nacelle by including the yaw angle (measured by the SCADA system). An example of the acceleration measured at the 4 levels during parked condition is shown in Figure 3.

Together with the acceleration signals, SCADA data are also gathered at a sampling frequency of 1 Hz to classify the operating condition of the turbine during the measurement. Moreover, for each 10 minute section, average information of the ambient data collected by the Meteo system are also stored to monitor the varying environmental conditions. In this paper, 20 10-minutes sections with the turbine in parked or idle condition are firstly analyzed. For the operational measurement, 3 clusters of 20 sections with different average wind speed were considered, to test different interactions between mode shapes and harmonic components.

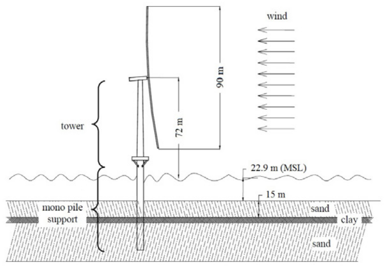

Figure 1: Schematic picture of the tested wind turbine.

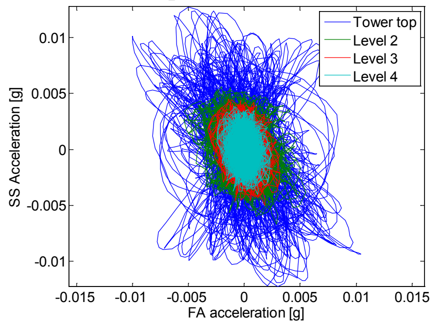

Figure 3: Examples of measured acceleration at the 4 levels in parked condition**.**

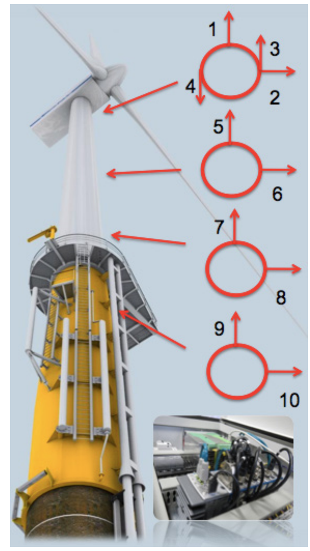

Figure 2: Measurement location and sensor orientations.

In [10], methodologies for automatic modal parameter identification in Operational Modal Analysis are presented and applied on the parked condition data. Together with the identification of the main tower modes in the 0-2 Hz frequency range, the correlation between modal parameters and environmental conditions (wind speed, wind and wave direction and tidal level) are investigated. In this paper, the frequency range of the analysis is extended up to 5 Hz, so that also the 3rd tower bending modes can be investigated.

3. OPERATIONAL MODAL ANALYSIS ON PARKED/IDLING CONFIGURATION

Among all data acquired after the measurement system was installed on the wind turbine, a period of 2 weeks when the turbine was idling or in parked condition was isolated. In parked/idling conditions the rotor of the turbine is rotating at less than 2 RPM and there are no rotor harmonics that might influence the OMA results. This paper will focus on the results up to 5Hz, so that the algorithm presented in [10] had to rerun for a bandwidth of 0.05-5Hz. Figure 4 gives the tracking results for this broader bandwidth.

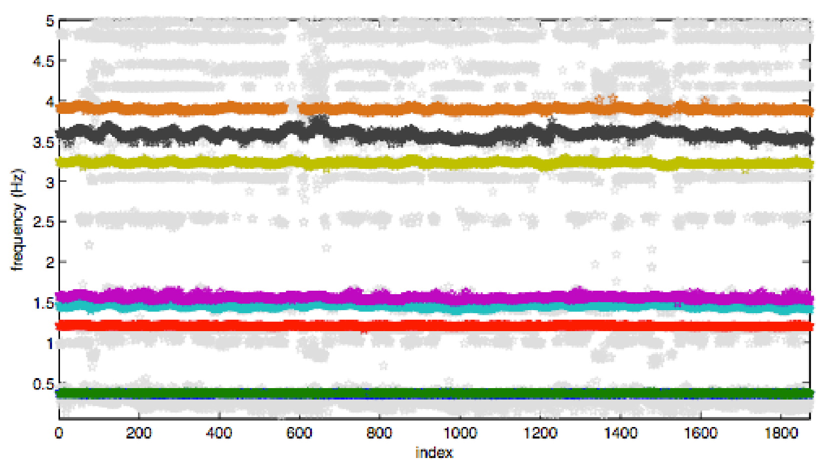

Figure 4: Results of the tracking algorithm [10] applied to a bandwidth of 0.05 – 5 Hz. (Color) tracked modes, (grey) identified modes by OMA that are not tracked.

Figure 4 shows that eight modes can be tracked over the two weeks of which three in the bandwidth of 2-5Hz. Additional structural modes, plotted in gray, are regularly identified, but are not tracked as they only appear intermittently and are less dominant in parked conditions. Note that the tracking algorithm of [10] relies on a set of reference mode shapes in order to track a single structural mode. In Figure 5 the reference modes used in [10] are given together with the three new modes.

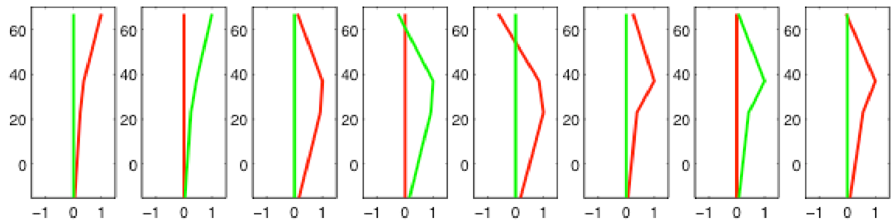

Figure 5: Used reference modes for the tracking of the 8 considered modes. (red : FA direction, green: SS direction). From left to right the reference mode shapes for the first bending modes (1st FA, 1st STS), a coupled blade-tower mode , the second bending modes (2nd STS, 2nd FA), another coupled mode and the third bending modes (3rd SS and 3rd FA).

Table 1 shows the results of tracking. In addition to previous studies the averaged results, over the two weeks, of the three modes from 2Hz-5Hz are also provided. It can be observed that the damping of the 3rd STS mode is considerably larger than the damping of the associated 3rd FA mode. This is consistent with the lower modes. In parked conditions the blades are pitched at 90° resulting in a larger blade surface in STS direction and consequently a larger aerodynamic damping [10]. The lower damping of the second coupled mode is also consistent with the lower damping of the first coupled mode.

Table 1: Mean results over the two weeks of parked conditions

Mode	**Success rate (%)**	**Mean freq (Hz)**	**Std freq (Hz)**	**Mean damp (%)**	**Std damp (%)**
1st FA	72	0.361	0.004	1.86	0.85
1st STS	50	0.366	0.005	2.49	0.97
Coupled	97	1.201	0.006	0.72	0.22
2nd STS	94	1.449	0.018	1.38	0.33
2nd FA	88	1.560	0.016	1.14	0.49
Coupled	98	3.226	0.018	0.79	0.25
3rd STS	99	3.579	0.045	2.25	0.65
3rd FA	91	3.893	0.018	1.20	0.25

4. DATA ANALYSIS IN OPERATIONAL CONDITIONS

To verify how standard Operational Modal Analysis techniques deal with data acquired with the turbine in operation, 3 datasets were shared, one with the turbine operating at the rated speed of 16 rpm and the other two with the rotor at an average speed between 14 and 12 and the last at 10 rpm. In this paper the analysis will focus on the first of the dataset were the rotor speed was roughly constant throughout the whole acquisition. This will simplify this preliminary analysis, since usually harmonic removal techniques work better when the rotational speed is roughly constant. On the other hand, in case of operations at variable speed, an accurate measured or estimated rpm trace is usually required to properly remove the tonal components. In a previous work from the authors [11] the influence of harmonic components on accelerations measured on the rotor during operation was analyzed. In case of blade accelerations, the harmonic components are also affected by aerodynamic forces and their removal is particularly critical. Moreover, blade modes are affected by gyroscopic effects. However, when focusing on the tower these effects are less critical, even though frequency variations due to different environmental conditions were analyzed in [10].

Figure 12 compares the accelerations in the two directions measured at the tower top in parked and operational conditions. In general, operational accelerations are obviously higher, but this is related to the fact that the wind speed was also the double. On the other hand, the blade passing in front of the tower represents a strong source of excitation, which is expected to appear clearly in the frequency domain in correspondence of the 3rd harmonic (3P) frequency. In the side to side direction, the difference between the two conditions is much lower, but higher peaks can also be observed.

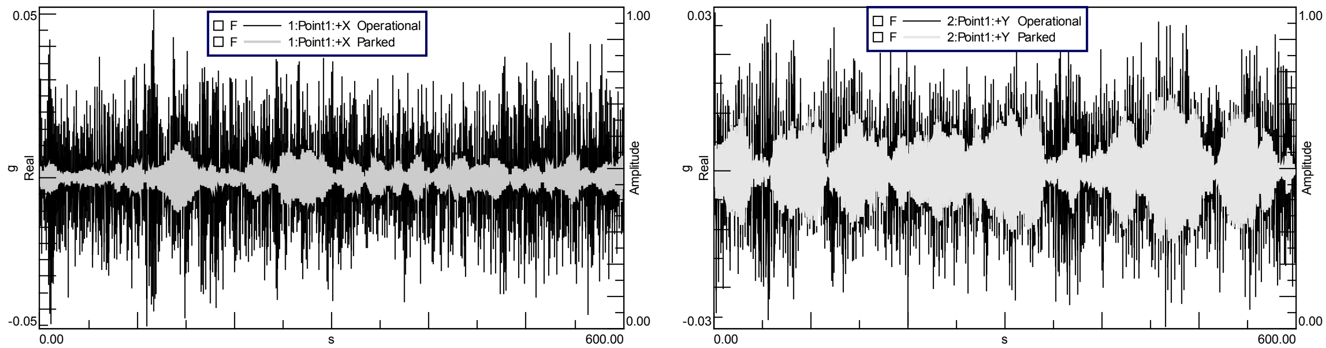

Figure 6: Comparison of FA(left) and STS(right) acceleration in parked and operational conditions.

To better understand the frequency components dominating the response of the signals in operating conditions, their Power Spectral Densities (PSDs) are computed and shown in Figure 7. As expected, all multiples of the 3rd harmonics are clearly appearing in the frequency domain as peaks. Strong components are associated to the 3P, 6P and 12P components. These results are obtained from the accelerations collected in the first 10 minutes dataset. Since PSD are obtained by averaging over the whole sequence, the peaks can be considered to be averaged values over the whole analysis time. It can immediately be observed by comparing parked and operational data that the amplitude and frequency of the peaks associated to the first 2 natural modes are comparable in both cases. On the other hand, for the rest of the frequency range, the operational levels are way higher, in particular in correspondence of harmonics. In the PSDs of the parked data, the peaks correspond to amplitude at resonance frequencies. However, we can clearly see that some of these peaks are very close to some of the harmonics which are visible in the operational data.

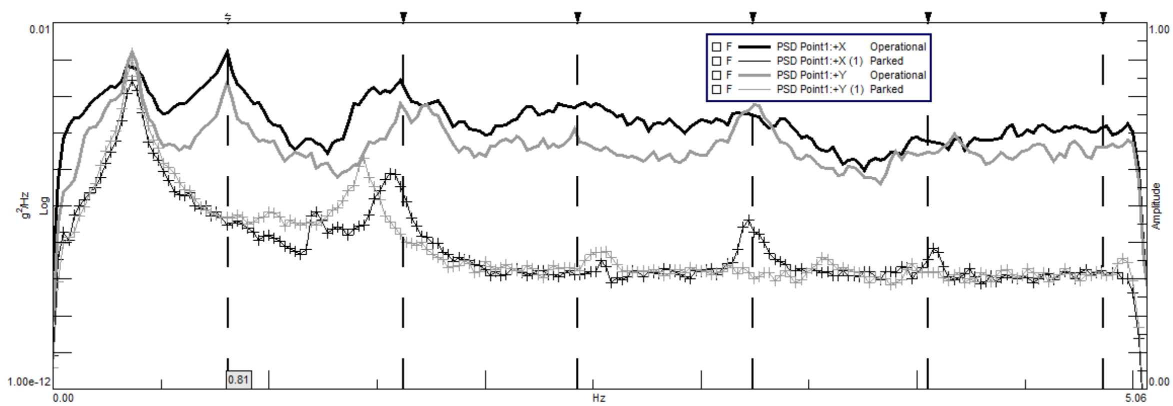

Figure 7: Comparison of acceleration PSDs in operational and parked condition. Vertical lines represent multiples of the 3P harmonic component.

4.1 IDENTIFICATION OF UNFILTERED DATA

To understand the influence of the harmonics on the modal parameter identification process, the raw data from the first dataset will be identified and the results compared with those obtained in parked conditions and summarized in Table 1. Both the PolyMAX and PolyMAX Plus algorithms were used to identify the modal model from the first section of the data. In the first case, to reduce the noise in the spectra above 3 Hz, a 10% exponential window was used to weight the correlation functions when computing the spectra. With the PolyMAX Plus, the property of the ML estimator to reduce the noise in the measured data was used so no additional window was applied.

In Figure 8, the stabilization obtained with the PolyMAX method applied on the operational data is shown. In general, the stabilization is relatively clear, but column of stable poles are found in correspondence of the 3P harmonic and its multiples. In general, one could not select these poles, but, if they are present, it is usually better to include them in the identification and distinguish them from true poles a-posteriori. Moreover, since they are identified as stables poles, there are good chances that automatic pole selection algorithms will select them. The list of identified modes both using PolyMAX and PolyMAX Plus is shown in Table 2. Finally, the mode shapes corresponding to the identified poles are shown in Figure 9.

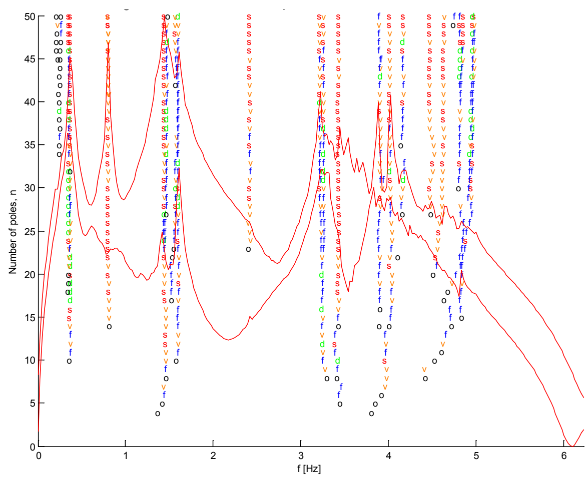

Figure 8: Example of stabilization diagram obtained with PolyMAX with unfiltered operational data.

Table 2: Summary of operational modes.

	PolyMAX		PolyMAX Plus	
Mode	Frequency [Hz]	Damping [%]	Frequency [Hz]	Damping [%]
1st FA	0.352	8.491	0.347	9.449
1st STS	0.372	2.444	0.369	1.425
ODS 3P	0.803	0.942	0.803	0.268
2nd FA	1.45	1.806	1.457	2.726
ODS 6P	1.602	0.377	1.605	0.033
ODS 9P	2.413	2.467		
ODS 12P	3.215	0.002	3.213	0.097
3rd FA	3.429	4.297	3.353	2.689
3rd STS	3.896	0.6	3.886	0.204
ODS 15P	4.013	0.272	4.016	0.181

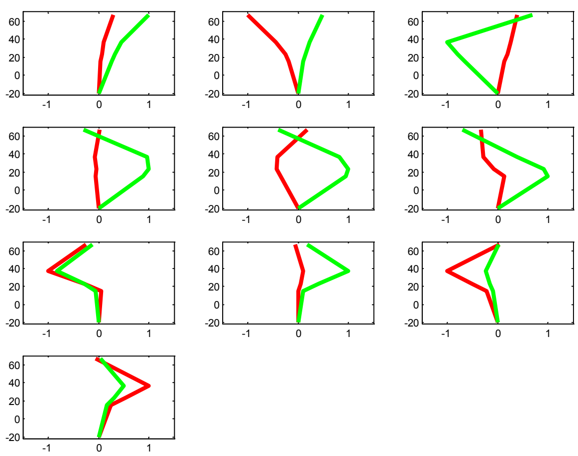

Figure 9: Operational mode shapes corresponding to PolyMAX estimated poles in Table 2.

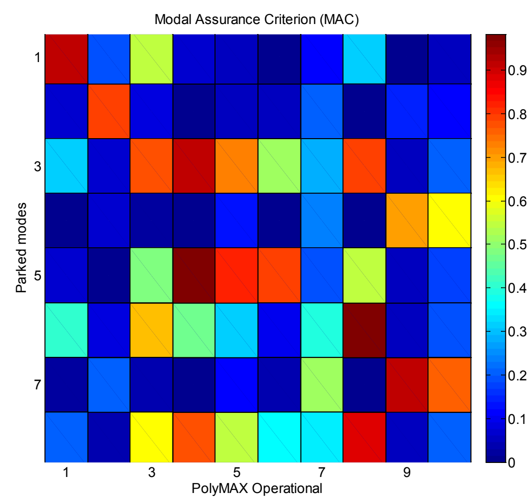

Figure 10: MAC between parked and operational modes.

The identified mode shapes can be graphically compared with those in Figure 5. Although some of the modes are the same as those in parked condition, there are other modes which were not present before and with a behavior similar to the one of some of the true modes. This means that some of them are operational deflection shapes due to the harmonic excitation which are however seen as poles by the estimation. A more quantitative comparison is shown in Figure 10, where the MAC between the reference parked condition modes and the one identified by the PolyMAX method applied on the operational data is shown. The first two tower bending modes are very well correlated with the corresponding parked modes. The 2nd side-to-side bending in the reference dataset doesn't correlate with any of the modes identified in operational conditions. This is probably due to a poor excitation of this specific mode during operations. For tracking purposes, the strong correlation of the 5th parked mode (2nd fore-aft) with both the 6P and 12P induced deflection shapes can pose some issue and lead to the identification of these shapes rather than the true mode in some specific condition. In an automated identification process, this could be avoided by selecting a frequency band around these harmonics and add a rule that automatically exclude poles (even with a very high MAC value) but falling in this region. The same could be applied for the 9th and 10th operational modes, which show strong correlation with the 3rd side-to-side bending modes. An additional problem related to the identified poles corresponding to harmonics is their relatively high damping values. Usually, these components are characterized by very sharp and narrow peaks, and even when poles are identified they have a damping of almost zero. However in this case damping is usually above 0.3% and is similar to the value of the physical poles. This is also clear when looking at the shape of the harmonics peaks in Figure 7. This is expect to lead to some issues when trying to remove the harmonics from the signals with some of the methods discussed in the next section.

4.2 HARMONIC REMOVAL TECHNIQUES

From the results discussed above, some of the dominant harmonic components, in particular the 6P and 15P, might affect the modal identification results due to their proximity to structural modes. In general, the possibility to track and remove these components from the acquired signals should improve the identification and tracking of modes of interest in structural and health monitoring applications. In this paper, two techniques to filter the data from these components are applied, namely the Angle-domain Time-Synchronous Averaging and the Cepstrum Editing Method, that are described in a previous publication by the authors [11].

Since the synchronous averaging is performed on the angle domain, the resampling need to be based on an accurate RPM trace [12], which is however not available in this case. To verify the assumption of constant rotational speed within the analyzed time signals, the initial 10-minutes section is cut in 5 smaller segments and the spectra of one of the signals computed by applying the FFT. The results are shown in Figure 15, where it can be observed that the peaks around 0.8 are not perfectly overlapped, meaning there are some small frequency fluctuations for the 3P components. However, the corresponding frequencies are varying in a range between 0.792 and 0.808 Hz, which is considered negligible. Based on this, it is assumed that the speed can be approximated as constant within each processing run and the corresponding RPM is computed by manually selecting the peak corresponding to the 3P component of the Autopower spectrum of the reference acceleration channel in the fore-aft direction. The assumption of constant speed during the analysis is confirmed by the fact that during all runs the selected 3P component appears always at the same frequency. Figure 16 shows the resulting obtained after applied the two methods on the first dataset. In general, TSA is able to maintain the random response of the signal reducing significantly the harmonic peaks. However, in particular for the 3P harmonic but also its multiples, a small peak remains with significant damping, which might be related to small frequency and amplitude modulation around the fundamental harmonic frequency. The cepstrum liftered with the exponential window, as already discussed in [11], lead to a general reduction of the power in the signals, which is however consistent in the all frequency range and between the different signals, so that the modes should remain unaffected. Natural frequencies and damping need to be corrected after identification to include the additional damping introduced by the exponential window.

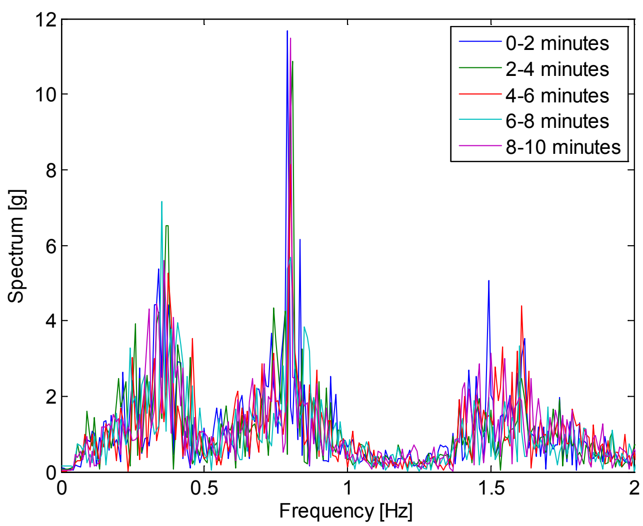

Figure 11: Comparison of spectrum of acceleration signals to verify assumption of constant rotational speed.

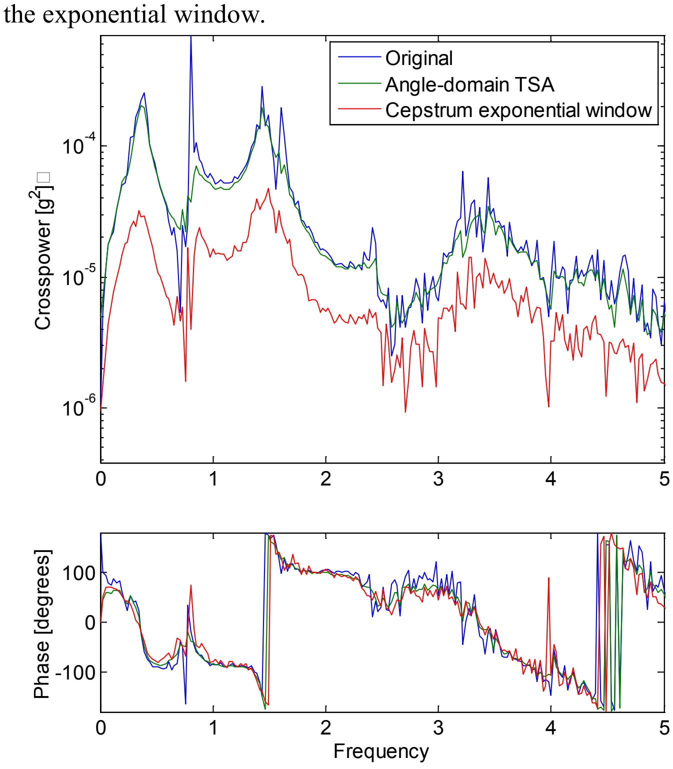

Figure 12: Crosspower comparison after Angle-domain TSA and Cepstrum Editing with exponential window.

The filtered data shown in Figure 12 can then be processed to obtained modal parameter estimates. From a theoretical point of view, if the harmonic components are properly removed from the signal, no more poles should be found by the estimation algorithm. Without showing the full results of the identification, in Figure 13 only the stabilization diagrams are shown. Comparing these diagrams with the one in Figure 8, it can immediately be observed that in general the harmonic components are not completely removed but poles are still found. The main different is that these values are less stable. Besides, the smoothing effect of the exponential window applied on the cepstrum and the consequently introduced damping can be seen in

Figure 13 right. In particular in the high frequency region the noise is strongly reduced, but on the other hand the 1st bending modes are also strongly affected by it (way less sharp peaks than with unfiltered or TSA-filtered data). Moreover the stabilization diagram is unclear and only few consecutive stable poles are found. Keeping these considerations in mind, the poles identified after filtering the data will be discussed and analyzed in the next section.

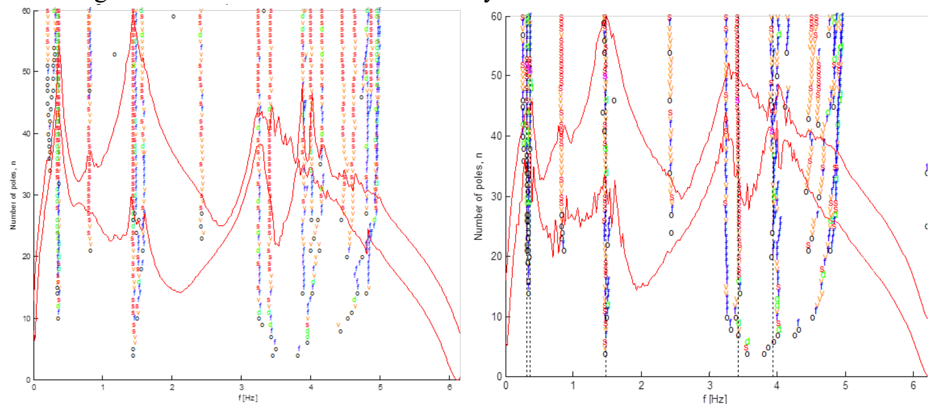

Figure 13: Stabilization diagrams for data filtered with TSA (left) and cepstrum editing(right).

5. AUTOMATED OPERATIONAL DATA PROCESSING

After assessing the identification results for a single run and comparing the results of removing the harmonic components from measured signals, an automated processing procedure is applied to these dataset. After choosing a reference dataset, an automated version of the PolyMAX and PolyMAX Plus methods are implemented which automatically select the stable poles in the stabilization diagram [13]. The modal models identified in the different runs are then compared with the reference modal model and only those with high correlation are kept.

First, the results of the PolyMAX algorithm on the unfiltered data are analyzed and shown in Figure 14. As before, a model order of 70 is used to build the stabilization diagram to ensure that as many poles as possible are selected. For the tracking algorithm, a reference modal model with only 5 modes is selected. These modes are the 1st, 2nd and 3rd fore-aft and 1st and 3rd side-to-side bending modes of the tower. As discussed, the 2nd side-to-side could not be identified while the coupled modes presented in Section 3 were not analyzed here. Choosing only these reference modes will ensure that regardless of the original number of poles, only with high correlation are kept. These results are shown in Figure 15, where the identified poles before and after tracking are shown. After tracking, all clusters of poles corresponding to multiples of the 3P harmonic are neglected. The high number of poles at the higher frequencies is related to the noise in the data. However, by adding on Figure 14 horizontal lines corresponding on the harmonic frequencies, some anomalies are found. For the 3rd and 5th modes, some of the identified poles lie exactly on the nearby harmonics. This can be related to what already observed in Figure 10 that deflection shapes nearby a mode have a shape which is highly correlated with it. Some method to avoid these poles to be selected as "true" poles will then be added in the future. However, in general, the 5 selected modes are identified in almost all datasets, showing how in operational conditions the excitation is stronger and it is easier to find the poles of interest.

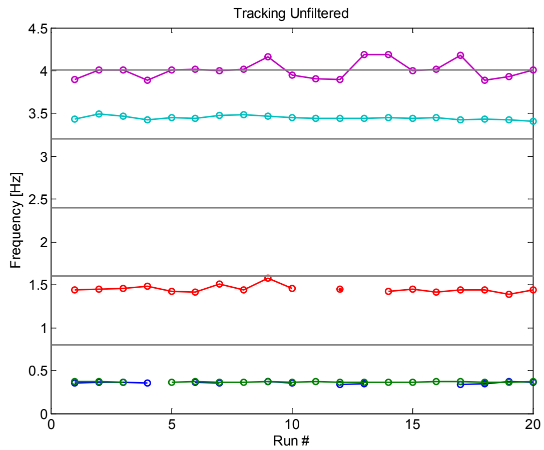

Figure 14: Results of automatic processing and tracking with PolyMAX for operational data.

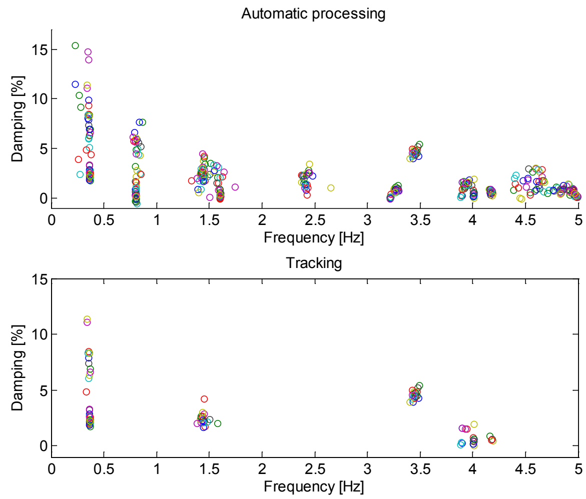

Figure 15: Results of automatic processing. Top: identified poles for automatic identification. Bottom: tracked poles based on the 5 reference ones.

The results obtained with the PolyMAX estimator and the same processing settings as before but applied on the data filtered with Angle-domain TSA and Cepstrum editing are now presented. The evolution of frequencies for the 5 reference modes are shown in Figure 16 and Figure 17. It can immediately be observed that editing the cepstrum with an exponential window gives significantly poorer results. In theory, the effect of the exponential window should be to leave the modal response in the cepstrum while filtering out all other components. In this case, however, where the 1st harmonic and the 1st modes are very close, the effect of the window to try to remove the harmonics is too strong. This can explain in particular the poor results in identifying the 1st tower bending modes. Also, when selecting manually the reference modes from the stabilization diagram using the data of the first run, the poles are less stable than for the other processing. However, this is the only case where none of the selected poles lay on a harmonic.

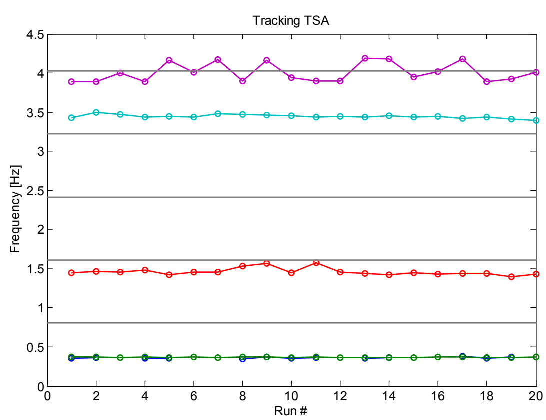

Figure 16: Evolution of frequency of the tracked modes after TSA.

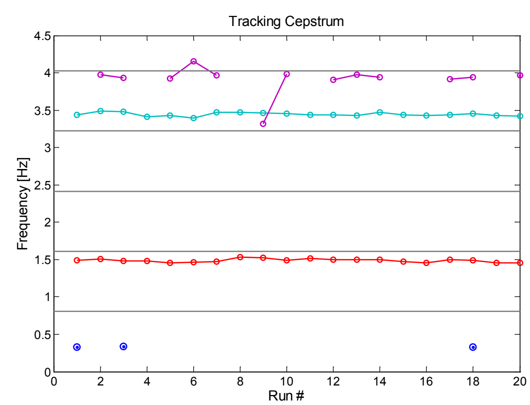

Figure 17: Evolution of frequency of the tracked modes after cepstrum editing.

By applying Angle-domain TSA, the results are more aligned with those obtained with the unfiltered data and the success rates for some of the modes are improved. A statistical comparison of the frequency and damping estimates with and without pre-filtering of the data is given in Table 5. In general, except the first tower fore-aft bending mode that has a success rate around 70%, all others modes are identified in more than 90% of the datasets. After filtering the data, the identification success rate is increased in all cases except the first mode, that shows a slight decrease but still above 50%. Moreover, as already said for the unfiltered data, some of the poles lay on one of the harmonic lines so these should not be considered as successfully identified. By excluding these modes from the tracking and recomputing the success rate, a significant improvement after TSA is applied can be observed in particular for the 3rd STS mode in Table 5.
Finally, it must be kept in mind that the success of tracking depends heavily on the dataset which is selected as reference for the analysis. This is the probable reason for the poor results on the first bending modes obtained with the cepstrum editing. The mode shapes selected as reference from the first datasets show poor correlation with the one form the others run. Finally,

the results in Table 5 show good agreement also in terms of standard deviation between the original and filtered data processing. This on one side means that the filtering is effective in not modifying the data, but also that probably the harmonics are not strongly influencing in this case the modal estimates.

Table 3: statistical comparison of modal estimates and tracking success rate for the original and preprocessed with Angle-domain TSA data. Between brackets are reported the success rates without including the poles at an harmonic frequency.

MODE	**1st FA**		**1st STS**		**2nd FA**		**3rd FA**		**3rd STS**	
	Original	A-TSA	Original	A-TSA	Original	A-TSA	Original	A-TSA	Original	A-TSA
MEAN FREQ	0.356	0.368	0.367	0.367	1.451	1.426	3.449	3.416	4.008	4.001
STD FREQ	0.010	0.008	0.002	0.003	0.040	0.046	0.022	0.023	0.098	0.117
MEAN DAMP	7.460	5.604	2.364	2.164	2.387	1.974	4.568	4.596	0.721	1.061
STD DAMP	2.180	1.673	0.437	0.465	0.555	0.666	0.367	0.435	0.568	0.583
MEAN MAC	0.898	0.962	0.863	0.736	0.982	0.994	0.966	0.971	0.943	0.921
SUCCESS RATE	**75%**	**65%**	**95%**	**100%**	**90% (85%)**	**100% (90%)**	**100%**	**100%**	**100% (55%)**	**100% (85%)**

5. CONCLUSIONS

This paper presents recent development of Operational Modal Analysis techniques and their application to wind turbine dynamic identification. Since the dynamic analysis and modal identification of wind turbines in operating conditions still represent a great challenge because of the assumptions required to apply OMA to these data, novel processing and estimation techniques need to be developed. In this context, the accelerations continuously acquired on the tower of an offshore wind turbine are analyzed, with the machine both in parked and operational condition to verify the influence of the harmonics introduced by the blade rotation on the identification results.

The accelerations acquired in parked conditions were identified first to obtain reference mode values. The analysis focused on the first 8 tower modes, which appear in the 0-5 frequency region. The results obtained applying advanced identification and automatic processing techniques were discussed and a reference modal model based on the averaged mode shapes from all processed run was identified. After this, operational data acquired with the turbine operating at rated speed (16 rpm) for a relatively long period of time were analyzed. By analyzing the frequency content of the data, a strong influence of the 3P harmonic components and its multiple was found. To reduce the influence of these components, harmonic filtering techniques such as Angle-domain Time Synchronous Averaging and Cepstrum Editing with an exponential window were applied. The data were again processing using the automatic modal identification and tracking tool developed and the results analyzed. The raw data and those pre-processed using TSA gave similar and very good results, both in terms of modal parameters as well as success rate. On the other hand, the exponential window applied on the cepstrum of the measured acceleration strongly affected the frequency content of the signals and the automated identification results were poor. However, one must be careful in simply tracking the modes with the proposed method since some of them are very close to harmonic components, which shows deflection shapes similar to the nearby modes. This was clear when overlapping the to the tracked modes lines corresponding to the dominant harmonics. If one really wants to track the modes for monitoring purposes, these poles should be not considered in the analysis.

The very good identification results are promising to continuously analyze data for monitoring of wind turbine also in operating conditions. The analysis will be however extended in the future to other datasets where the turbine is operating at different regimes, where a stronger interaction between the modes and harmonic components may reduce significantly the mode tracking results. In this case, also the ability to automatically distinguish a mode from a forced response due to an harmonic component need to be implemented.

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